MARKED-UP VERSION OF

ENGLISH TRANSLATION OF

INTERNATIONAL APPLICATION

AS ORIGINALLY FILED

DESCRIPTION

MECHANICAL QUANTITY SENSOR

TechnicalBACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] ——The present invention relates to a mechanical quantity sensor configured to detect a mechanical quantity such as acceleration, angular acceleration, angular velocity, or load.

Background2. Description of the Related Art

[0002] ——A known acceleration sensor including piezoelectric vibrators is disclosed in Japanese Unexamined Patent Document 1Application Publication No. 2002-243757 filed by the assignee/applicant of this application.

[0003] ——The known acceleration sensor outputs an acceleration detection signal in the following manner. A bridge circuit is configured with two piezoelectric vibrators receiving stresses generated by acceleration in opposite directions and two load impedances each including a capacitor. A voltage-dividing impedance circuit is provided between the average output terminals of the bridge circuit. An oscillating circuit is configured by feeding back a

signal from the voltage-dividing point of the voltage-dividing impedance circuit to the connection point of the two piezoelectric vibrators by a feedback signal processing circuit. The phase difference between oscillation output terminals from the average outputs of the bridge circuit is detected as an acceleration detection signal.

[0004]   ———Since the acceleration sensor according to Japanese Unexamined Patent ~~Document 1~~Application Publication No. 2002-243757 includes a bridge circuit configured with two piezoelectric vibrators and two load impedances each including a capacitor, the phase difference between oscillation outputs does not equal zero unless the bridge is at equilibrium. In other words, even if the stresses applied to the two piezoelectric vibrators both equal zero, the output of the acceleration sensor does not equal zero. Furthermore, the known acceleration sensor has a problem in that it is difficult to control the phase shifting circuit so that acceleration sensitivity is maximized.

[0005]   ———Since the piezoelectric vibrators and the circuits are expected to be disposed more than 10 cm apart, a detection method that does not cause problems even when the piezoelectric vibrators and the circuits are disposed more than 10 cm apart has been ~~in need~~urgently needed.

[0006]   ———The assignee/applicant of this application has disclosed in Japanese Unexamined Patent Application

Publication No. 2003-254991a mechanical quantity sensor that has solved the above-identified problem ~~in Patent Document 2~~. The mechanical quantity sensor includes two piezoelectric vibrators receiving stresses generated by acceleration in opposite directions, a voltage signal applying circuit configured to apply a common voltage signal to the two piezoelectric vibrators, an electric current-to-voltage converter circuit configured to convert the current signals flowing through the piezoelectric vibrators into voltage signals, and a phase difference signal processor circuit configured to detect the phase difference between output signals from the electric current-voltage converter circuit and to output a mechanical quantity signal.

[0007]   ——The mechanical quantity sensor according to Japanese Unexamined Patent ~~Document 2~~Application Publication No. 2003-254991 is described with reference to Fig. 9.

[0008]   ——In Fig. 9, an acceleration detection element 10 includes two piezoelectric vibrators Sa and Sb receiving stresses generated by acceleration applied in opposite directions. The piezoelectric vibrators Sa and Sb are connected in series to resistors RLa and RLb, respectively. A current-to-voltage converter/signal adder circuit 11 converts the current signals flowing through the piezoelectric vibrators Sa and Sb of the acceleration detection element 10 into voltage signals so as to output an

Sa signal and an Sb signal, respectively. Furthermore, the current-to-voltage converter/signal adder circuit 11 outputs an added signal obtained by adding the Sa and Sb signals.

[0009] ——A voltage amplifier/amplitude limiter circuit 12 amplifies the voltage of the added signal, limits the amplitude, and outputs a voltage signal Vosc to the acceleration detection element 10. The voltage signal Vosc is applied to a common connecting point of the piezoelectric vibrators Sa and Sb.

[0010] ——A phase-difference-to-voltage converter circuit 13 generates a voltage signal that is proportional to the phase difference between the Sa and Sb signals converted into voltage signals.

[0011] ——An amplifier/filter circuit 14 amplifies the voltage signal converted by the phase-difference-to-voltage converter circuit 13 by a predetermined gain, eliminates unwanted frequency band components, and outputs the obtained signal as an acceleration detection signal.

[0012] ——In the circuit shown in Fig. 9, the resonant frequencies of the piezoelectric vibrators Sa and Sb are made equal so that the frequency Vosc is set as a resonant frequency fr(0) for both of the piezoelectric vibrators Sa and Sb. In this way, when stresses having reversed phases, such as compression (pulling) and pulling (compression), are applied to the piezoelectric vibrators Sa and Sb,

respectively, an output signal can be obtained from the
amplifier/filter circuit 14.

[0013]· ——The V_{osc} is a feedback voltage signal of a
self-excited oscillator circuit configured of a loop of the
piezoelectric vibrators Sa and Sb, the current-to-voltage
converter/signal adder circuit 11, and the voltage
amplifier/amplitude limiter circuit 12.

~~Patent Document 1: Japanese Unexamined Patent Application
Publication No. 2002-243757~~
~~Patent Document 2: Japanese Unexamined Patent Application
Publication No. 2003-254991~~

~~Disclosure of Invention~~
[0014] ——As illustrated in Fig. 9, resistors RLa and
RLb are connected in series to piezoelectric vibrators Sa
and Sb, respectively. Therefore, the damping ratio
increases, and, thus, the change rate of acceleration
detection sensitivity can be reduced in a wide temperature
range. As a result, the sensor can be stabilized with
respect to environmental temperature.

[0015] ——Fig. 10(A) shows the relationship between the
magnitude of a resistor connected to the piezoelectric
vibrators and the change rate of the temperature
characteristics of the acceleration detection sensitivity (G
sensitivity). The value of the damping ratio represented by

the horizontal axis is obtained as 'damping ratio=RL/resistance at resonance,' where RLa=RLb=RL, when the resonance of the piezoelectric vibrators at resonant frequency is defined as the resonant resistance. The vertical axis represents the change rate range ((maximum value)-(minimum value)) of the acceleration detection sensitivity for the entire operational temperature range (-40°C to +85°C). As the damping ratio is increased, the change rate range of the acceleration detection sensitivity decreases and ~~stabilized~~stabilizes with respect to temperature change.

[0016] ――――According to an experiment carried out by the inventor, the sensor operated normally when the damping ratio was ~~set to~~ 2. However, when the damping ratio was increased to 6, abnormal oscillation was observed and the sensor was incapable of normally operating as a mechanical quantity sensor. The abnormal oscillation was caused by a decrease in response at a predetermined oscillation frequency due to an increase in the damping ratio, reducing the difference to the response at an unwanted oscillation frequency.

[0017] ――――Figs. 10~~(B)~~ and 10~~(C)~~ show the frequency characteristics of the open loop gain of a self-exciting oscillating circuit including the acceleration detection element 10, the current-to-voltage converter/signal adder

circuit 11, and the voltage amplifier/amplitude limiter circuit 12, shown in Fig. 9, where the damping ratio is 2 and 6, respectively. Here, 'S' represents the response at a predetermined oscillation frequency and 'N' represents the response at an unwanted oscillating frequency band higher than the frequency N with a high gain. In general, to prevent abnormal oscillation, the difference between the gain Gs of the response S at the predetermined oscillation frequency and the maximum gain Gn of the response N at the unwanted frequency band must be 10 dB or more. In this known example, when the damping ratio was ~~set as~~ 2, the difference was 11.5 dB, which did not ~~causing~~cause abnormal oscillation. However, when the damping ratio was ~~set at~~ 6, the difference is 6.3 dB, ~~causing~~ which caused abnormal oscillation.

[0018] ——The above-described problem is not limited to a sensor for detecting acceleration but is a problem that is common to sensors in which electric currents flow through piezoelectric vibrators in accordance with a mechanical quantity, such as angular acceleration, angular velocity, or load.

[0019] ——To ~~suppress~~minimize the signal intensity in the unwanted frequency band, a frequency filter may be provided in the oscillation loop of the self-exciting oscillating circuit. However, since a frequency filter has

phase characteristics, the rate change of the phase (slope of the phase) with respect to a frequency change of a feedback signal ~~steeply.~~is steep. Moreover, since there is a fluctuation in the phase characteristics of the frequency filter, if only the frequency filter is ~~merely~~ provided, the effect of the fluctuation of the phase characteristics of the frequency filter will be great, causing a new problem in that fluctuation and temperature change rate of the detection sensitivity will be increased.

~~An object of the present invention is~~

SUMMARY OF THE INVENTION

[0020]   In order to overcome the problems described above, preferred embodiments of the present invention provide a mechanical quantity sensor that is capable of solving the problem of abnormal oscillation and obtaining stable detection sensitivity for a mechanical quantity in a wide temperature range.

[0021]   ~~Accordingly, the~~ According to a preferred embodiment of the present invention, a mechanical quantity sensor includes two piezoelectric vibrators configured to receive stresses caused by a mechanical quantity in opposite directions, a voltage signal applying circuit configured to apply a voltage signal to both of the piezoelectric vibrators, a current-to-voltage converter circuit configured to convert electric current signals flowing through the

piezoelectric vibrators into voltage signals, and a phase difference signal processing circuit configured to detect the phase difference between the output signals from the current-to-voltage converter circuit and output a mechanical quantity detection signal, wherein resistors are inserted in electric current paths of the piezoelectric vibrators, and wherein. Furthermore, the voltage signal applying circuit includes, a voltage amplifier circuit configured to amplify the voltage of an added signal corresponding to an added value of currents flowing through the piezoelectric vibrators, an amplitude limiter circuit configured to limit the amplitude of the voltage signal output from the voltage amplifier circuit to a predetermined value, a phase control circuit configured to detect the phase difference between a feedback voltage signal applied to both the piezoelectric vibrators and the added signal and control the phase of the feedback voltage signal so that the phase difference equals a predetermined value, and a filter circuit configured to suppressminimize unwanted frequency components of the feedback voltage signal, and wherein the mechanical quantity sensor is oscillated by the piezoelectric vibrators, the voltage amplifier circuit, the amplitude limiter circuit, the phase control circuit, and the filter circuit.

[0022]   ──According to this unique structure, unwanted frequency components of the feedback voltage signal for the

piezoelectric vibrators are ~~suppressed~~minimized by the
filter circuit and the phase of the feedback voltage signal
is controlled so that the phase difference of the feedback
signal to the piezoelectric vibrators and the added signal
corresponding to an added value of electric currents flowing
through the piezoelectric vibrators equals a predetermined
value. Therefore, the slope of the phase is prevented from
becoming steep due to the filter circuit. In this way, the
fluctuation and the temperature change rate is reduced.

[0023]   ————According to another preferred embodiment of
the present invention, the filter circuit is a low-pass
filter having a pass band including an oscillation frequency,
and the phase control circuit includes a phase-difference-
to-voltage converter circuit configured to convert the phase
difference between the added signal and the feedback voltage
signal into a voltage signal, a comparator circuit
configured to compare an output signal from the phase-
difference-to-voltage converter circuit and a reference
signal, and an all-pass filter including a voltage
controlled resistance circuit whose impedance is changed in
accordance with an output voltage from the comparator
circuit, ~~and an~~wherein the phase of the all-pass filter
~~whose phase~~ is changed in accordance with the impedance of
the voltage controlled resistance circuit.

[0024]   ————In this way, by providing an all-pass filter

at the phase control circuit, converting the phase difference of the added signal and the feedback voltage signal into a voltage signal, and controlling the phase of the all-pass filter in accordance with the result of comparing the voltage signal and a reference signal, stable oscillation can be maintained by controlling the phase while maintaining the gain at a constant value.

[0025]   ——According to another preferred embodiment of the present invention, the phase control circuit is configured to control the phase difference between the feedback voltage signal and the added signal so that detection sensitivity of a mechanical quantity is maximized.

[0026]   ——In this way, the detection sensitivity of the mechanical quantity is maximized.

[0027]   ——In preferred embodiments of the present invention, the mechanical quantity is, for example, acceleration, angular acceleration, angular velocity, or load.

[0028]   ——According to another preferred embodiment of the present invention, the damping ratio is increased by connecting the resistors to the piezoelectric vibrators receiving stresses generated by a mechanical quantity in opposite directions. In this way, the range of the change rate of the acceleration detection sensitivity decreases, stabilizing the sensor with respect to temperature change.

Moreover, the phase difference of the feedback voltage

signal applied to both of the piezoelectric vibrators and

the added signal of the currents flowing through the

piezoelectric vibrators ~~is~~are maintained at ~~a~~ predetermined

values and unwanted frequency components of the feedback

voltage signal ~~is suppressed.~~are minimized. Consequently,

the slope of the phase is prevented from becoming steep due

to providing the filter circuit ~~being provided~~, and the

fluctuation of the detection sensitivity and the temperature

change rate is reduced. Moreover, by controlling the phase,

the phase of the feedback voltage signal with respect to the

acceleration detection element is stabilized ~~and~~, the

oscillation is stabilized, and the noise components included

in the mechanical quantity detection signal is

~~suppressed.~~minimized. Accordingly, for example, the time

constant of the low-pass filter for ~~suppressing~~minimizing

the noise components can be ~~set at~~a small value, and, thus,

the response can be improved.

[0029] ~~————~~According to another preferred embodiment of

the present invention, the filter circuit configured to

~~suppress~~minimize unwanted frequency components of the

feedback voltage signal is a low-pass filter including the

oscillation frequency in its passing band and an all-pass

filter is provided at the phase control circuit configured

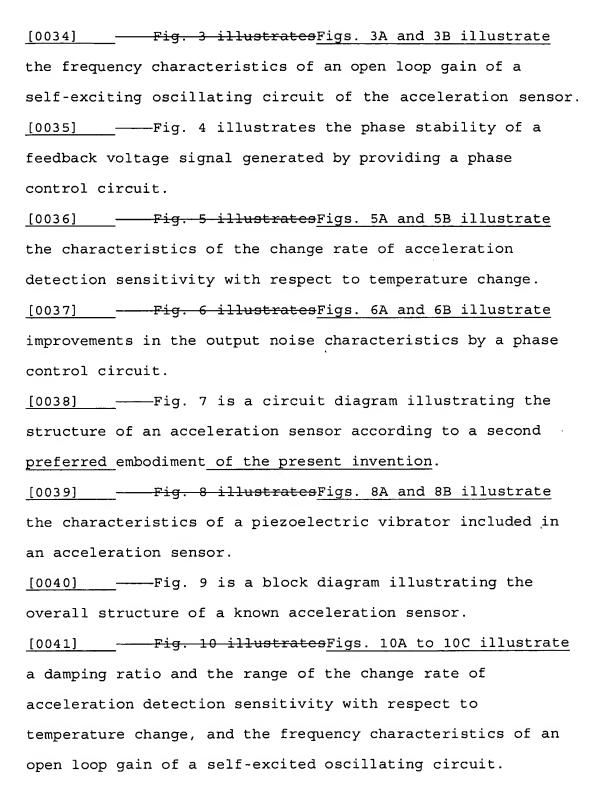to maintain the phase difference of the feedback voltage

signal applied to both of the piezoelectric vibrators and the added signal of the current flowing through the two piezoelectric vibrators at a predetermined value. In this way, the phase can be controlled while the gain is maintained constant. Thus, stable oscillation can be maintained.

[0030]   ——According to another preferred embodiment of the present invention, ~~by~~due to the phase control circuit, the phase difference between the feedback voltage signal and the added signal is controlled so that the detection sensitivity of the mechanical quantity is maximized. Therefore, a mechanical quantity can always be detected at maximum sensitivity.

[0031]   Other features, elements, steps, advantages and characteristics of the present invention will become more apparent from the following detailed description of preferred embodiments thereof with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0032]   ——Fig. 1 is a block diagram illustrating the overall structure of an acceleration sensor according to a first preferred embodiment of the present invention.

[0033]   ——Fig. 2 is a detailed circuit diagram of the acceleration sensor.

[0034]   ——Fig. 3 illustratesFigs. 3A and 3B illustrate the frequency characteristics of an open loop gain of a self-exciting oscillating circuit of the acceleration sensor.

[0035]   ——Fig. 4 illustrates the phase stability of a feedback voltage signal generated by providing a phase control circuit.

[0036]   ——Fig. 5 illustratesFigs. 5A and 5B illustrate the characteristics of the change rate of acceleration detection sensitivity with respect to temperature change.

[0037]   ——Fig. 6 illustratesFigs. 6A and 6B illustrate improvements in the output noise characteristics by a phase control circuit.

[0038]   ——Fig. 7 is a circuit diagram illustrating the structure of an acceleration sensor according to a second preferred embodiment of the present invention.

[0039]   ——Fig. 8 illustratesFigs. 8A and 8B illustrate the characteristics of a piezoelectric vibrator included in an acceleration sensor.

[0040]   ——Fig. 9 is a block diagram illustrating the overall structure of a known acceleration sensor.

[0041]   ——Fig. 10 illustratesFigs. 10A to 10C illustrate a damping ratio and the range of the change rate of acceleration detection sensitivity with respect to temperature change, and the frequency characteristics of an open loop gain of a self-excited oscillating circuit.

Best Mode for Carrying Out the Invention

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0042]   First, the characteristics of a piezoelectric vibrator included in an acceleration sensor according to ana preferred embodiment of the present invention will be described with reference to Fig. 8.s. 8A and 8B. Fig. 8(A) shows a change in the phase of an electric current (i.e., admittance phase) corresponding to a change in the frequency of a voltage source of the circuit shown in the drawing. The solid line represents a state in which stress is not applied, whereas the dotted line represents a state in which stress is applied. Fig. 8(B) is an enlarged view of the resonant frequency band shown in Fig. 8(A).

[0043]   In Fig. 8s. 8A and 8B, the frequencies having a phase of zero degrees are the resonant frequencies of a piezoelectric vibrator. As apparent from Fig. 8s. 8A and 8B, the resonant frequency changes from fr(0) to fr(x) when stress is applied. If the frequency of the voltage source is fixed at fr(0), the phase changes from $\phi(0)$ to $\phi(y)$ when stress is applied.

[0044]   The structure of an acceleration sensor according to the first preferred embodiment of the present invention will be described with reference to Figs. 1 to 6B.

[0045] ——Fig. 1 is a block diagram illustrating the overall structure of the acceleration sensor. An acceleration detection element 10 includes piezoelectric vibrators Sa and Sb receiving stresses generated by acceleration applied in opposite directions. A current-to-voltage converter/signal adder circuit 11 converts the current signals flowing through the piezoelectric vibrators Sa and Sb of the acceleration detection element 10 into voltage signals and outputs Sa and Sb signals. The current-to-voltage converter/signal adder circuit 11 also outputs an added signal obtained by adding the Sa and Sb signals.

[0046] ——A voltage amplifier/amplitude limiter circuit 12 amplifies the voltage of the added signal and limits its amplitude.

[0047] ——A phase control circuit 20 controls the phase of the output signal from the voltage amplifier/amplitude limiter circuit 12. A filter circuit 17 attenuates output signals from the phase control circuit 20 that have frequencies higher than a predetermined cutoff frequency.

[0048] ——The output signal V_{osc} from the filter circuit 17 is fed back to the acceleration detection element 10. More specifically, a loop including the piezoelectric vibrators Sa and Sb, the current-to-voltage converter/signal adder circuit 11, the voltage amplifier/amplitude limiter circuit 12, the phase control circuit 20, and the filter

circuit 17 configure a self-exciting oscillating circuit. The feedback voltage signal V_{osc} is applied to the common connecting point of the piezoelectric vibrators Sa and Sb.

[0049]   ——The phase control circuit 20 includes a phase-difference-to-voltage converter circuit 15 and a phase shifter circuit 16.   The phase-difference-to-voltage converter circuit 15 generates a voltage signal corresponding to the phase difference between the added signal from the current-to-voltage converter/signal adder circuit 11 and the feedback voltage signal V_{osc}, which is an output signal from the filter circuit 17.   The phase shifter circuit 16 shifts the phase of the output signal from the voltage amplifier/amplitude limiter circuit 12 by an amount corresponding to the voltage signal output from the phase-difference-to-voltage converter circuit 15.

[0050]   ——The filter circuit 17 ~~suppresses~~minimizes the frequency components in the unwanted frequency band, as shown in Fig. 10~~(B)~~, by attenuating frequencies higher than a cutoff frequency in the vicinity of a predetermined oscillation frequency (a resonant frequency fr of the piezoelectric vibrator).   As a result, the maximum gain Gn in the unwanted frequency band, shown in Fig. 10~~(B)~~, is decreased so that the difference between gains Gs and Gn at the predetermined resonant frequency fr increases.

[0051]   ——Although the filter circuit 17 causes the

phases of input and output signals ~~being~~ to be different from each other, the phases of an added signal corresponding to the added current value of the piezoelectric vibrators Sa and Sb and the feedback voltage signal V_{osc} applied to both of the piezoelectric vibrators Sa and Sb are controlled by the phase control circuit 20 so that the phase difference is constantly maintained at a predetermined value. In this way, the phase change due to the filter circuit 17 is cancelled out. As a result, the self-exciting oscillating circuit can be stably oscillated even when the values of resistors RLa and RLb are increased to increase the damping ratio.

[0052] ——The phase-difference-to-voltage converter circuit 13 corresponds to the "phase difference signal ~~processor~~processing circuit" according to various preferred embodiments of the present invention and generates a voltage signal proportional to the phase difference between the signal Sa and the signal Sb, which are voltage signals obtained by converting the current signals.

[0053] ——The amplifier/filter circuit 14 amplifies the voltage signal obtained by the phase-difference-to-voltage converter circuit 13 by a predetermined gain, eliminates unwanted frequency band components, and outputs an acceleration detection signal.

[0054] ——In the circuit shown in Fig. 1, the resonant frequencies of the piezoelectric vibrators Sa and Sb are

made equal so that the frequency V_{osc} is set as the resonant frequency fr(0) for both of the piezoelectric vibrators Sa and Sb. In this way, when stresses having reversed phases are applied to the piezoelectric vibrators Sa and Sb, an output signal substantially proportional to the applied stresses can be output from the amplifier/filter circuit 14.

[0055]   ——The frequency V_{osc} is not limited to the resonant frequency for the piezoelectric vibrators Sa and Sb, and so long as the frequency V_{osc} is set to a frequency that has frequency-to-phase characteristics represented by a substantially straight line, as shown in Fig. 8s. 8A and 8B, the acceleration signal can be detected. The maximum acceleration detection sensitivity is obtained when the frequency V_{osc} equals the resonant frequency of the piezoelectric vibrators Sa and Sb. However, for practical use, the frequency may be set so that the admittance phase is within about ±45 degrees.

[0056]   ——Even when the resonant frequencies of the piezoelectric vibrators Sa and Sb are not the same, the sensitivity will be suitable for practical use so long as the frequency V_{osc} is set so the admittance phases of the piezoelectric vibrators Sa and Sb are within about ±45 degrees. More preferably, the frequency V_{osc} may be set to a value between the resonant frequency of the piezoelectric vibrator Sa and the resonant frequency of the piezoelectric

vibrator Sb.

[0057] ————Since stresses having reversed phases, such as compression (pulling) and pulling (compression), are applied to the piezoelectric vibrators Sa and Sb, respectively, the changes in the characteristics of the piezoelectric vibrators Sa and Sb are always in reversed phases. Thus, when the signals from the piezoelectric vibrators Sa and Sb are added, they cancel out each other. Accordingly, the added signal output from the current-to-voltage converter/signal adder circuit 11 will always have the same characteristics regardless of the applied acceleration. Therefore, even when the characteristics of the piezoelectric vibrators Sa and Sb change due to the applied acceleration, the frequency V_{osc} does not change.

[0058] ————As shown in the phase characteristics of the piezoelectric vibrator in Fig.——8s. 8A and 8B, there are two bands (resonant frequency band and anti-resonant frequency band) in which the admittance phase is within about ±45 degrees. In the anti-resonant frequency band, since impedance of the piezoelectric vibrator is high, the electric current flowing through the current-to-voltage converter/signal adder circuit 11 is reduced. As a result, gain is reduced, and the piezoelectric vibrator does not oscillate.

[0059] ————On the contrary, in the resonant band, since

impedance of the piezoelectric vibrator is low, the electric
current flowing through the current-to-voltage
converter/signal adder circuit 11 is increased. As a result,
gain is increased, and the oscillation of the triangular
prism 12 oscillates stablyis more stable.

[0060]   ——In the resonant band, the impedance of the
piezoelectric vibrator and the input impedance of the
current-to-voltage converter/signal adder circuit 11 are
both low and can be easily matched with each other. Thus,
the C/N ratio can be easily improved.

[0061]   ——Next, Fig. 2 shows specific, preferred
circuits in the acceleration sensor shown in Fig. 1. In the
current-to-voltage converter/signal adder circuit 11, a
first current-to-voltage converter circuit includes an
operational amplifier OP1 and a feedback resistor R21, a
second current-to-voltage converter circuit includes an
operational amplifier OP2 and a feedback resistor R22, and
an adder circuit includes an operational amplifier OP3 and
feedback resistors R23, R24, and R25.

[0062]   ——The filter circuit 17, as shown in Fig. 2,
includes an operational amplifier OP6, resistors R51 and R52,
and capacitors C3 and C4 constitutingwhich define a
secondary low-pass filter. In other words, in a frequency
band higher than the cutoff frequency, the gain is
attenuated by about 40 dB as the frequency is increased by

about ten times.

[0063]   ——Figs. 3-(A)- and 3-(B)- show the frequency
characteristics of a—an open loop gain of a self-exciting
circuit including the filter circuit 17 when damping ratios
are set at 2 and 6, respectively. When the frequency
characteristics shown in Figs. 3-(A)- and 3-(B)- are compared
with the characteristics shown in Figs. 10-(B)- and 10-(C)-, it
is apparent that the maximum gains Gn in the unwanted
frequency bands are significantly attenuated and the
differences between the maximum gains Gn and the gains Gs in
the predetermined frequency bands are about 25.9 dB and
about 17.6 dB, respectively. Accordingly, by increasing the
values of the resistors RLa and RLb, shown in Fig. 1,
abnormal oscillation can be prevented even when the damping
ratio is increased. More specifically, as shown in Fig.
3-(B)-, even when the damping ratio is set at 6, the
difference between the maximum gain Gn of the response N in
the unwanted frequency band and gain Gs is about 17.6 dB.
This value is about 7.6 dB higher than 10 dB that is a value
known as an indication of abnormal oscillation.

[0064]   ——In Fig. 2, the phase shifter circuit 16
includes a comparator circuit 161, a reference voltage
circuit 160, and an all-pass filter 162. The comparator
circuit 161 preferably includes an operational amplifier OP4,
a resistor R30, and a capacitor C1. The comparator circuit

161 compares a reference voltage generated by the reference voltage circuit 160 and a voltage output by the phase-difference-to-voltage converter circuit 15 and outputs a voltage signal obtained by amplifying the voltage difference with a predetermined voltage gain.

[0065]   ——The all-pass filter 162 includes a voltage controlled resistance circuit (VCR) whose impedance is changed in accordance with an output voltage from the comparator circuit, wherein the phase of the all-pass filter is changed in accordance with the impedance of the voltage controlled resistance circuit. As characteristics of the all-pass filter 162, the gain in all frequency bands is constant and the phase can be changed from 0 to 180 degrees.

[0066]   ——Fig. 4 shows the effect of the phase control circuit 20, shown in Fig. 1. If the characteristics of the acceleration detection element 10 is are included, the phase characteristics of the entire sensor will become complex. Therefore, characteristics of the circuits not including the acceleration detection element 10 are shown here. In a known circuit not including the phase control circuit 20, the slope of the phase change with respect to slope of the frequency change is steep, as shown in by the line B. However, by providing the phase control circuit 20, the slope of the phase change with respect to the slope of the frequency change is significantly reduced in the

predetermined phase control frequency band, as shown ~~in~~by
the line A.

[0067] ————A phase control band is determined by a
predetermined frequency band centered on the oscillation
frequency (resonant frequency fr of the piezoelectric
vibrator). If the slope of the phase change with respect to
the slope of frequency change is not steep in the phase
control band, a fluctuation in the acceleration detection
sensitivity can be kept small even if the resonant
frequencies of the piezoelectric vibrators Sa and Sb
fluctuate due to manufacturing factors. By providing the
phase control circuit 20, the phase of the feedback voltage
signal V_{osc} applied to the two piezoelectric vibrators can be
~~set to~~ a predetermined phase. According to this preferred
embodiment, the phase is ~~set to~~ six degrees. Since the
phase of the self-exciting oscillating circuit is zero
degrees as a total, the phase of the acceleration detection
element 10 is -6 degrees. This means that the phase of the
electric current flowing through the acceleration detection
element 10 is -6 degrees with respect to the applied voltage.
This ~~point~~ is the point where the slope of the current phase
of the acceleration detection element 10 according to this
preferred embodiment becomes the straightest and the
steepest. By controlling the phase so that such a point is
obtained, the acceleration detection sensitivity is

maximized and linearity is improved. The above-mentioned "6

degrees" of the phase is a value ~~set~~ for this preferred

embodiment and may be changed in accordance with the

characteristics of the acceleration detection element 10

and/or the intended use of the sensor.

[0068]   ~~Fig. 5 shows~~Figs. 5A and 5B show an

improvement in the change rate of the acceleration detection

sensitivity corresponding to temperature change. ~~(A)~~Fig. 5A

shows the change rate of the acceleration detection

sensitivity corresponding to temperature change when the

damping ratio is 2. ~~(B)~~Fig. 5B shows the change rate of the

acceleration detection sensitivity corresponding to

temperature change when the damping ratio is 6. In either

case, three samples were used for measurement. In a known

circuit, the sensor can not function as an acceleration

sensor due to abnormal oscillation when the damping ratio is

6, whereas, according to this preferred embodiment, the

sensor operates stably even when the damping ratio is ~~set to~~

6. Moreover, according to this preferred embodiment, the

range of change rate of the acceleration detection

sensitivity can be maintained within about ±2% in a wide

temperature range of about -40°C to ~~about 90°C.

[0069]   ~~Fig. 6 shows~~Figs. 6A and 6B show an

improvement in the output noise characteristics by the phase

control circuit 20. Fig. 6~~(A)~~ shows the noise

characteristics of a known circuit, and Fig. 6 (B) shows the noise characteristics of a circuit according to a preferred embodiment of the present invention. Here, the output noise is a noise component observed in the output of the phase-difference-to-voltage converter circuit 13, as shown in Fig. 1. In the known circuit not including the phase control circuit 20, as shown in Fig. 6 (A), the amplitude of a random output noise is great, whereas, in the acceleration sensor according to this the present preferred embodiment, the observed output noise is suppressed reduced by about one half. This is possibly because the phase control circuit 20 stabilizes the phase of the feedback voltage signal V_{osc} applied to the acceleration detection element 10, stabilizing the oscillation as a result. Since, the output noise component is reduced in this way, the time constant of the low-pass filter configured to suppress minimize the output noise component in the amplifier/filter circuit 14 can be set as a small value. As a result, the response of the sensor is improved.

[0070]   Next, an acceleration sensor according to a second preferred embodiment will be described with reference to Fig. 7.

[0071]   The structure of the current-to-voltage converter/signal adder circuit 11 of the acceleration sensor according to the second preferred embodiment differs from

that of the sensor shown in Fig. 2. The structure of the
current-to-voltage converter/signal adder circuit 11
according to the second preferred embodiment adds voltages
generated in resistors RLa and RLb when electric currents Ia
and Ib flowing through piezoelectric vibrators Sa and Sb,
respectively, of the acceleration detection element 10 flow
through resistors RLa and RLb respectively. Operational
amplifieramplifiers OP1 and OP2 each have significantly high
input impedance and constitutemake up a voltage follower
circuit the having a gain of that is 1. An operational
amplifier OP3 and resistors R25 and R26 constitutedefine a
non-inverting amplifier circuit. The non-inverting
amplifier circuit and resistors R23 and R24 constitutedefine
an adder circuit that receives an added signal generated
from the output voltages of the operational amplifiers OP1
and OP2.

[0072] ———In Fig. 2, the resistors RLa and RLb are
connected in series to the acceleration detection element 10,
whereas, in Fig. 7, the resistors RLa and RLb are connected
between the inputs of the operational amplifier OP1 and OP2,
respectively, and the ground.

[0073] ———The first and second preferred embodiments
describe acceleration sensors configured to detect a
difference in stresses applied to the piezoelectric
vibrators Sa and Sb due to acceleration. A sensor for

detecting other mechanical quantities can be configured by configuring the piezoelectric vibrators Sa and Sb such that stresses in opposite directions are applied to the piezoelectric vibrators Sa and Sb. For example, if a difference in stresses applied to the piezoelectric vibrators Sa and Sb is generated due to angular acceleration, the sensor can be used as an angular acceleration sensor. If a difference in stresses applied to the piezoelectric vibrators Sa and Sb is generated due to angular velocity, the sensor can be used as an angular velocity sensor. Similarly, if a difference in stresses applied to the piezoelectric vibrators Sa and Sb is generated due to load, the sensor can be used as a load sensor.

Industrial Applicability

[0074] ————According to preferred embodiments of the present invention, a mechanical quantity, such as acceleration, angular acceleration, angular velocity, or load, of a moving object can be detected, and the condition of the object and the condition of apparatuses related to the object can be detected.

[0075] ——While the present invention has been described with respect to preferred embodiments thereof, it will be apparent to those skilled in the art that the disclosed invention may be modified in numerous ways and may assume

many preferred embodiments other those specifically set out and described above. Accordingly, it is intended by the appended claims to cover all modifications of the present invention which fall within the true spirit and scope of the present invention.